Magnetic Fusion Science, ITER, and the U.S. Role in Fusion Development

for

NERSC USERS' Group

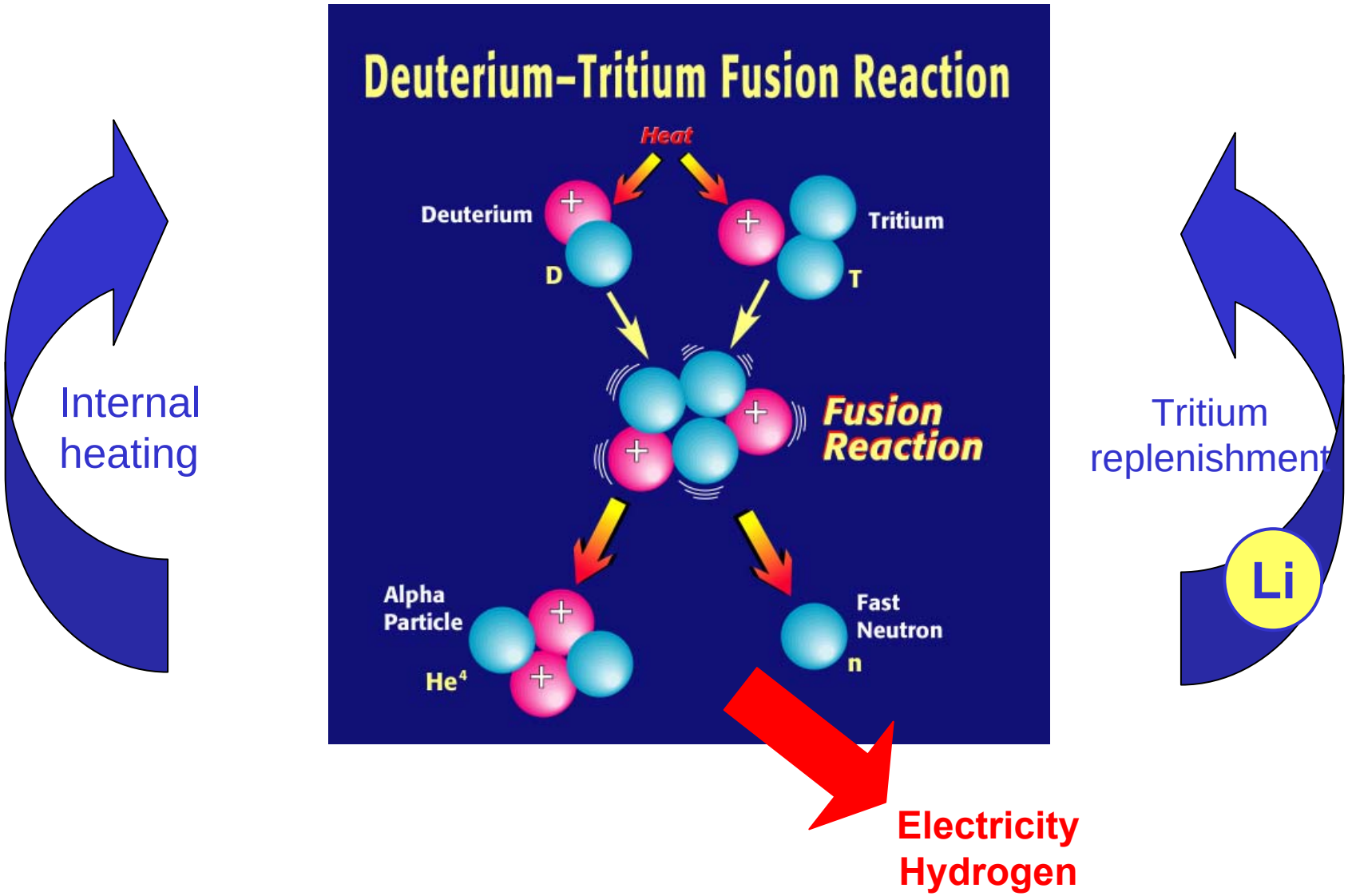
by

R. J. Hawryluk
Deputy Director
DOE Princeton Plasma Physics Laboratory
June 12, 2006

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Fusion is an Attractive Long-term Form of Nuclear Energy

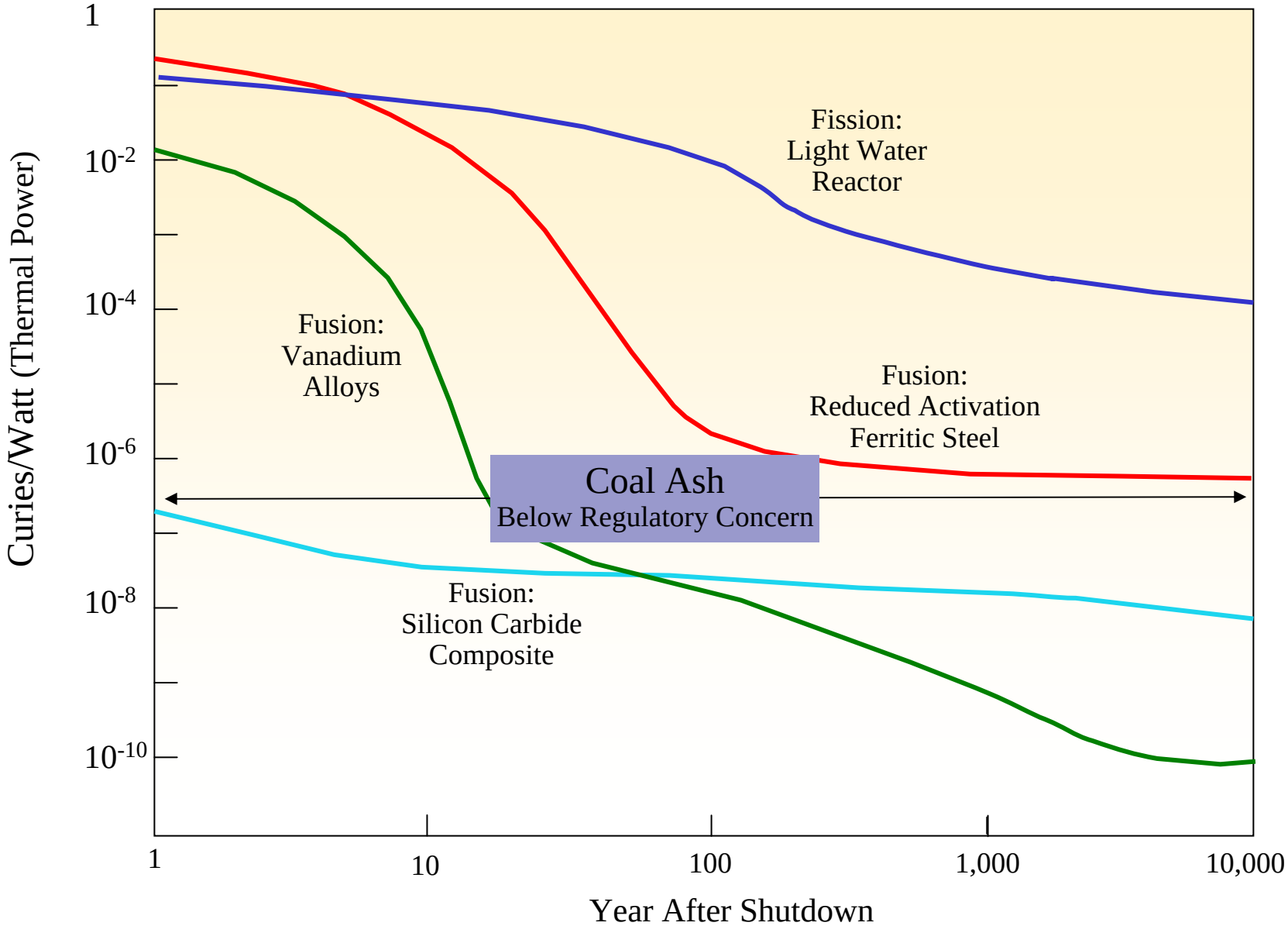


Fusion can be an Abundant, Safe and Reliable Energy Source

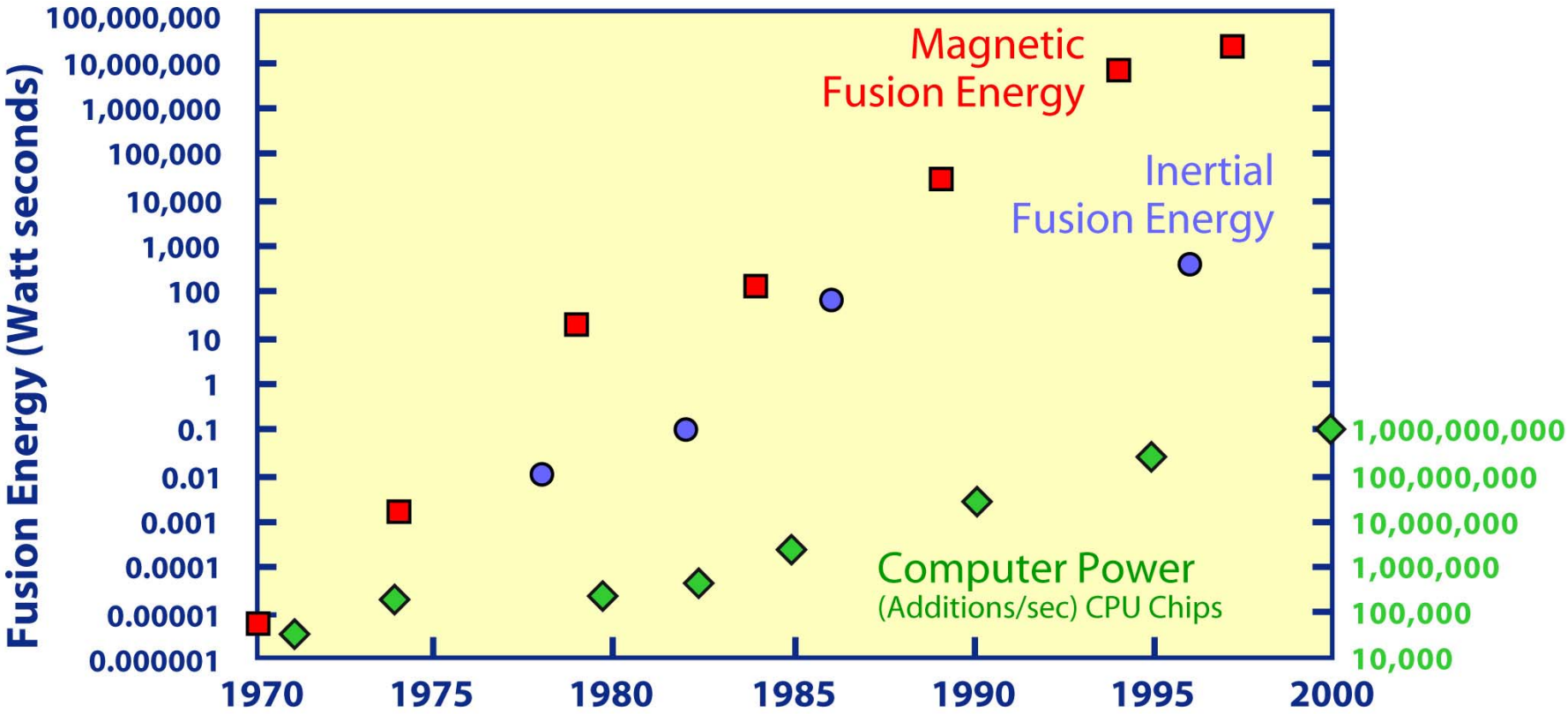
- Worldwide long-term availability of low-cost fuel.
- No acid rain or CO_2 production.
- No possibility of runaway reaction or meltdown.
- Short-lived radioactive waste.
- Low risk of nuclear proliferation.
- Steady power source, without need for large land use, large energy storage, very long distance transmission, nor local CO_2 sequestration.
- Estimated to be cost-competitive with coal, fission.

Complements nearer-term energy sources.

Fusion has Low Long-Lived Waste



Progress in Fusion has Outpaced Computer Speed

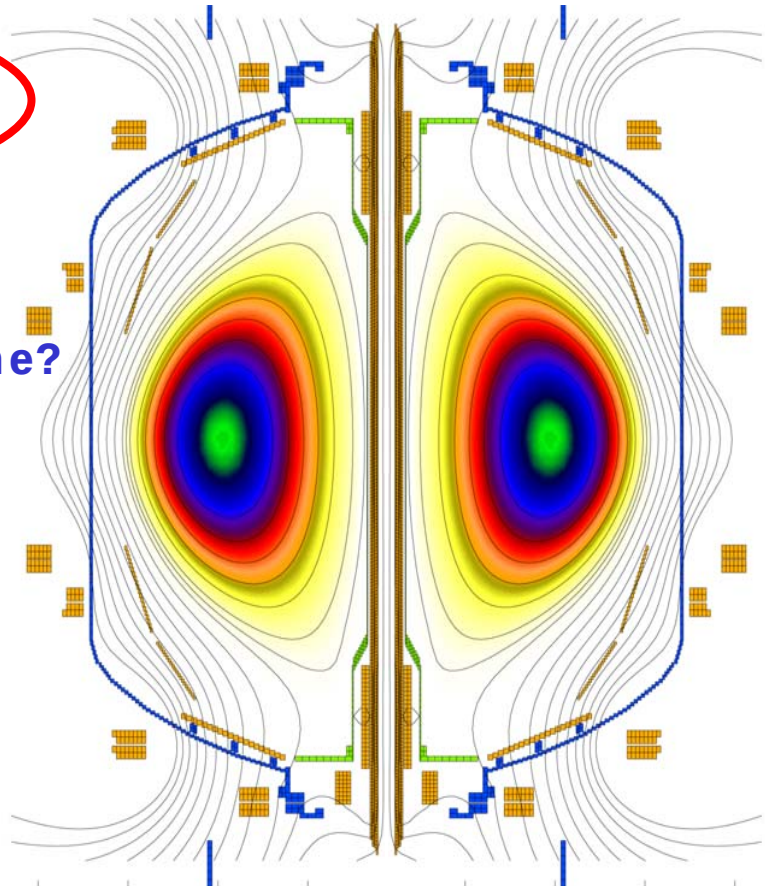


ITER will produce over 200GJ of heat from fusion, demonstrating the scientific and technological feasibility of magnetic fusion.
NIF will produce over 2MJ of fusion heat, demonstrating the scientific feasibility of inertial fusion.

Fusion Plasma Science Challenges

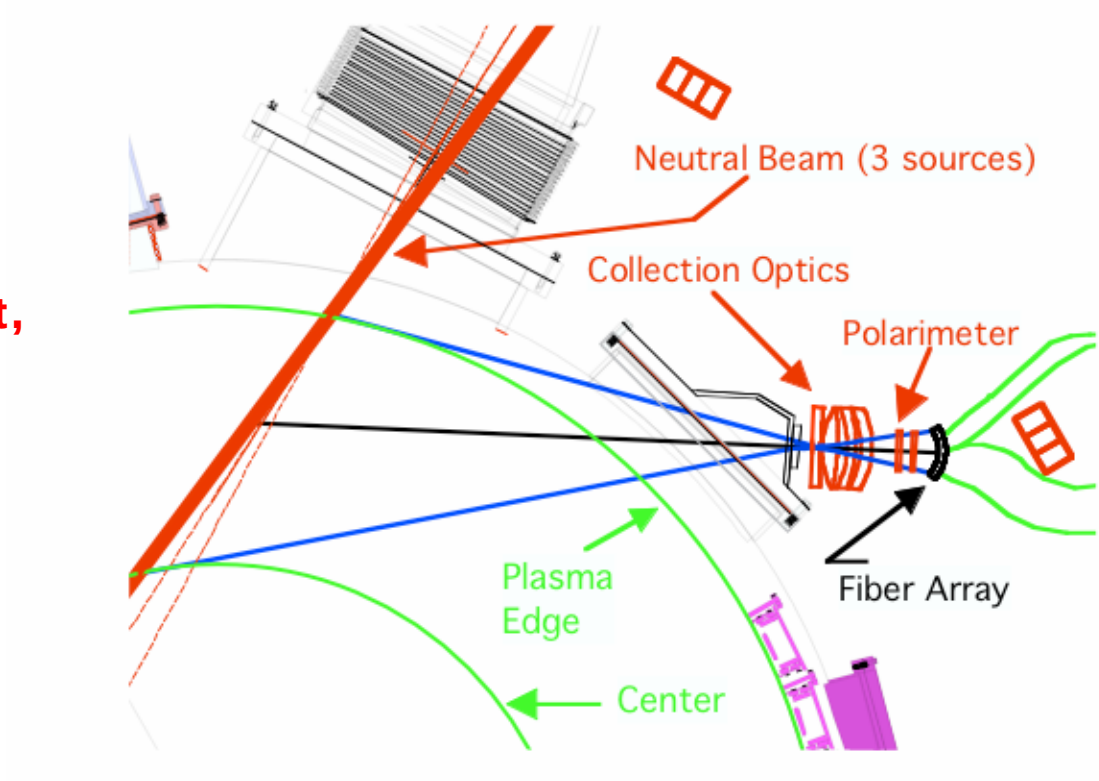
NAS Plasma Science Committee

- **Global Stability**
  - What limits the pressure in plasmas?
    - Solar flares
- **Wave-particle Interactions**
  - How do hot particles and plasma waves interact in the nonlinear regime?
    - Magnetospheric heating
- **Microturbulence & Transport**
  - What causes plasma transport?
    - Accretion disks
- **Plasma-material Interactions**
  - How can high-temperature plasma and material surfaces co-exist?
    - Micro-electronics processing



Motional Stark Effect Measurements of Field Angle has Revolutionized Stability Studies

- **Motional Stark Effect depends on v x B ⇒ E.**
  - Linear effect in D_0 beam injected into plasma, crossing magnetic field.
- **Allows highly localized measurement of B field tilt, to a fraction of a degree.**
- **Revolutionized stability studies by allowing detailed measurements of internal magnetic fields.**
  - Typical confidence level in pressure limits ~ 15%



Ideal MHD Stability is Well Understood

$$\delta W = \frac{1}{2}\int dr^3 \left\{ \frac{|\delta B|^2}{\mu_o} + \frac{B^2}{\mu_o}|\nabla \cdot \xi_\perp + 2\xi_\perp \cdot \kappa|^2 + \gamma p|\nabla \cdot \xi|^2 - J_{\parallel}(\xi_\perp \times b)\cdot \delta B - 2(\xi_\perp \cdot \nabla p)(\kappa \cdot \xi_\perp) \right\}$$

current limit pressure limit

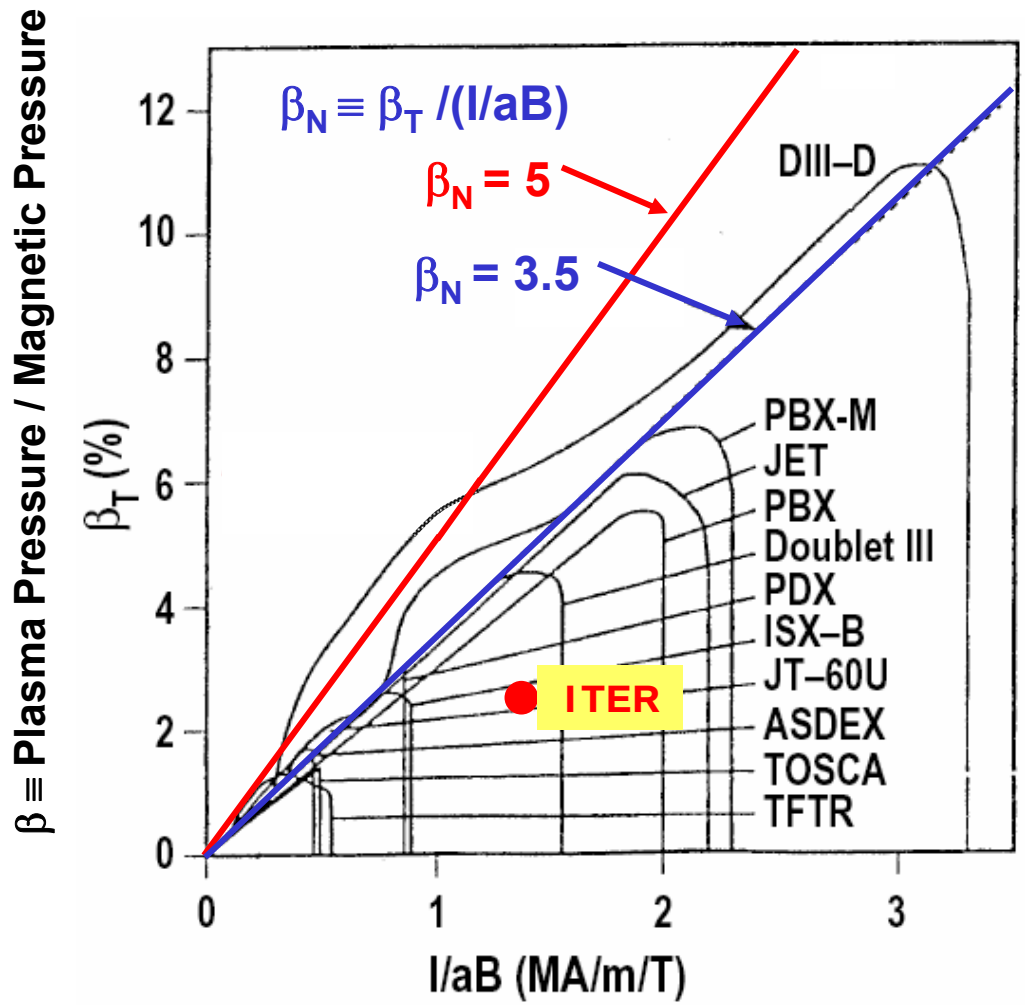
Ideal MHD → no breaking of magnetic field lines, plasma frozen to (moving) field.

Violation of linear ideal MHD stability results in rapid disruption of tokamak plasmas by global displacement.

for R/a ~ 3:

β_N = 3.5 ~ no-wall limit

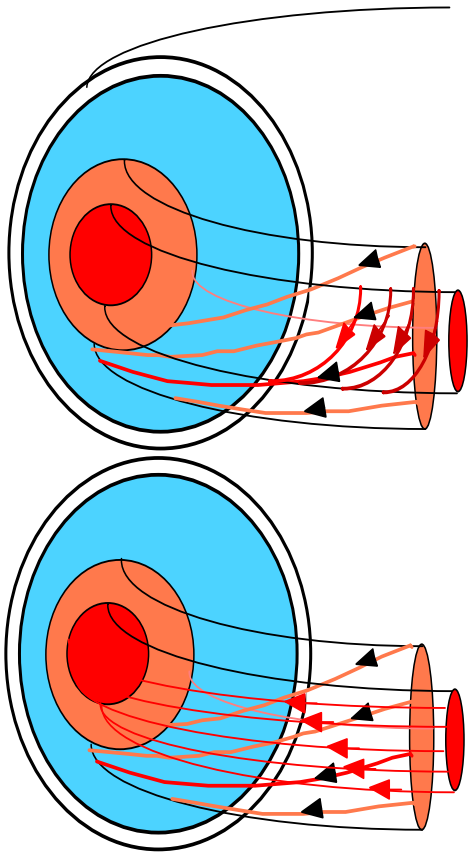
β_N = 5.0 ~ ideal-wall limit (Resistive Wall Mode instability in between.)



Plasma Edge is Simulated using 3-D Non-linear Simulations

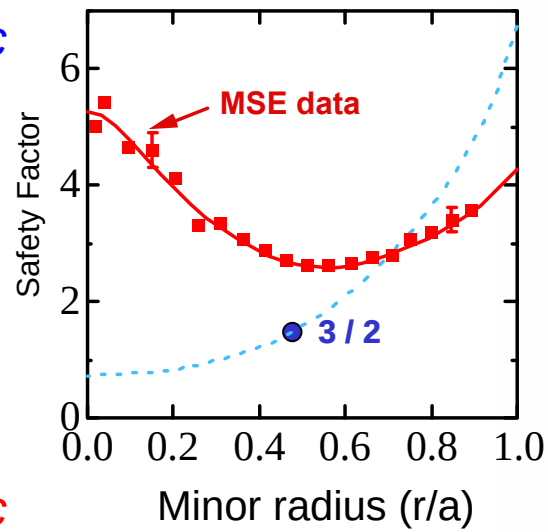
QuickTime™ and a
MPEG-4 Video decompressor
are needed to see this picture.

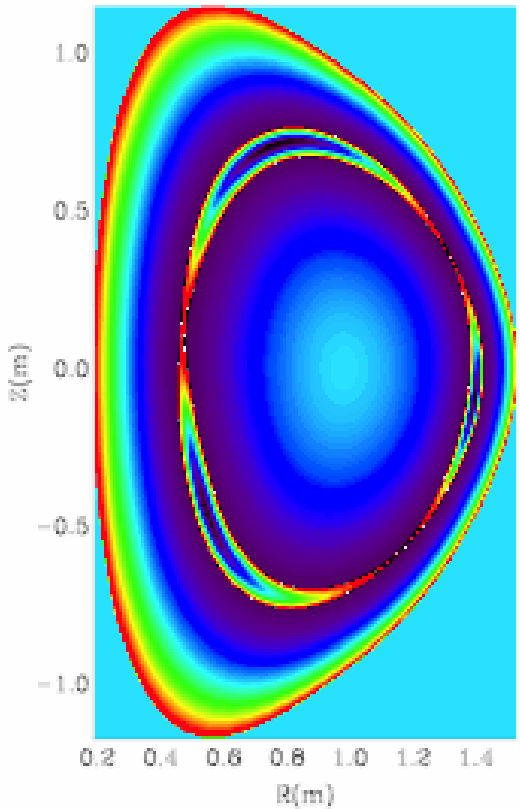
Current-carrying Systems are Subject to Reconnection – "Tearing Modes"



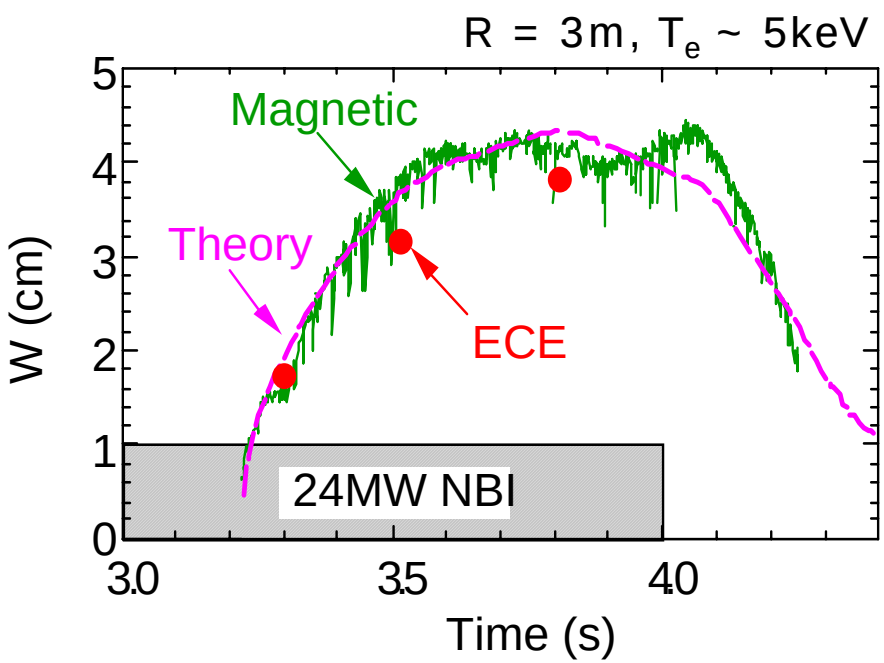
Normal magnetic shear

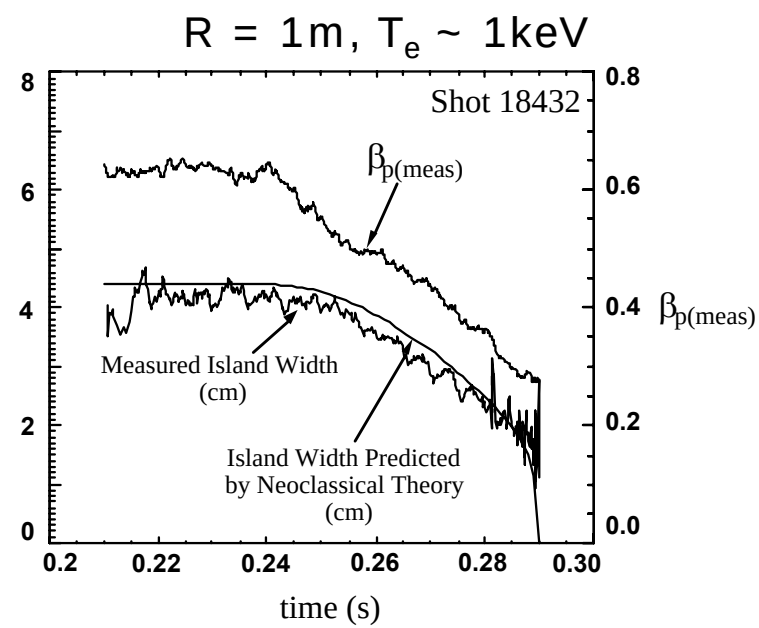
Reverse magnetic shear





Theory Accurately Predicts Growth of Neoclassical Tearing Modes (NTM)

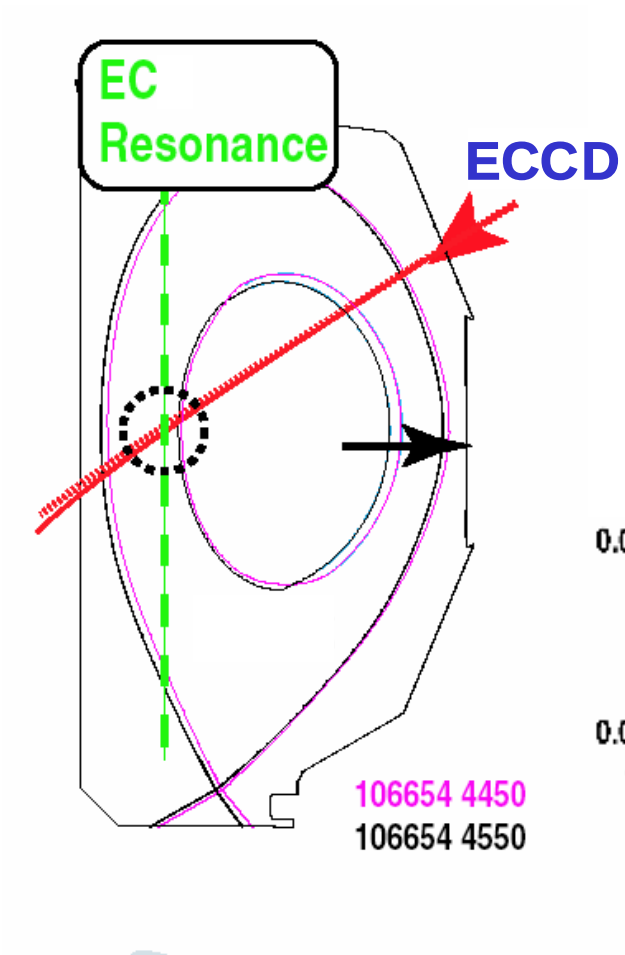


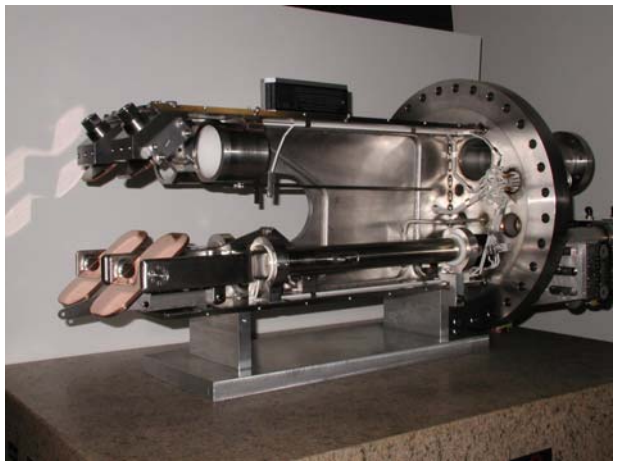


Bootstrap current + normal shear drives NTM's.

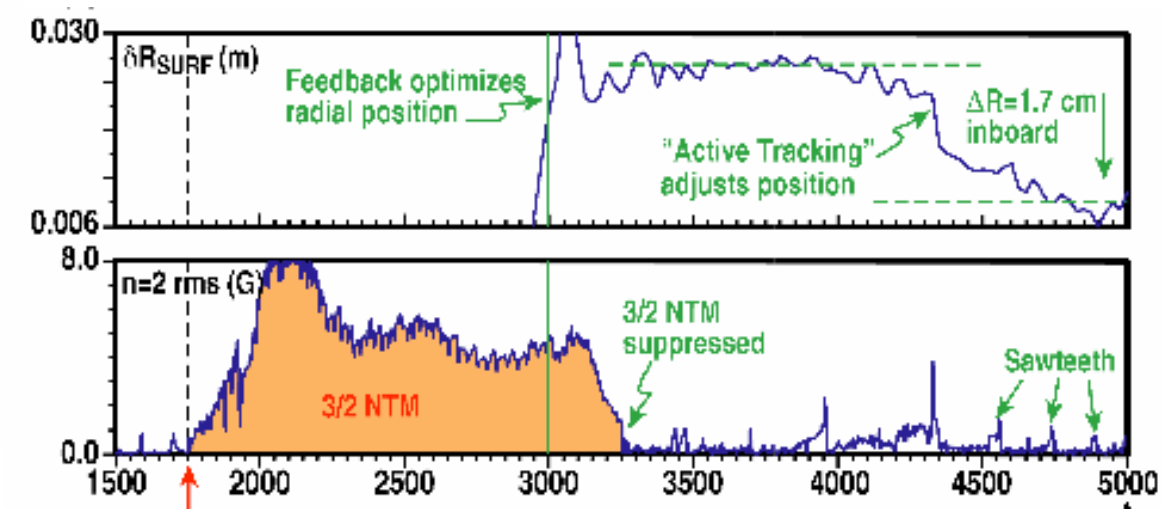
- Agrees to factor of ~2 with neoclassical resistivity, over a wide range of plasma parameters.
- Reverse shear stabilizes NTM's, as predicted.
- Strong implications for toroidal system optimization.

Replacing Bootstrap Current in Islands Stabilizes Neoclassical Tearing Modes





Steerable Electron Cyclotron Current Drive wave launcher.

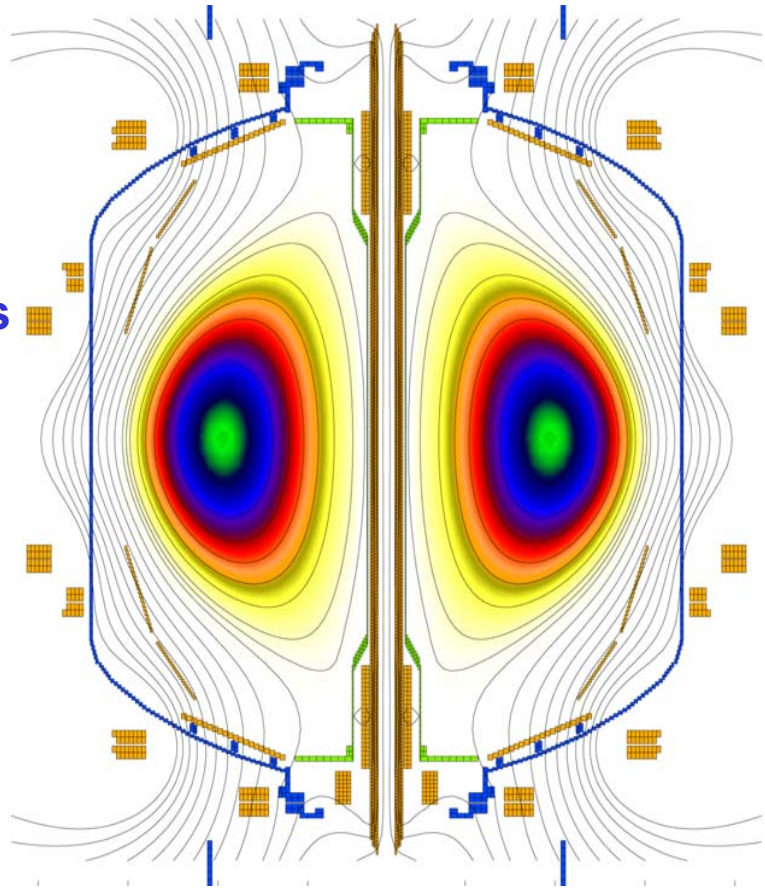


ITER will have ECCD for NTM control.

Plasma Science Challenges

NAS Plasma Science Committee

- **Global Stability**
  - What limits the pressure in plasmas?
    - Solar flares
- **Wave-particle Interactions**
  - How do hot particles and plasma waves interact in the nonlinear regime?
    - Magnetospheric heating
- **Microturbulence & Transport**
  - What causes plasma transport?
    - Accretion disks
- **Plasma-material Interactions**
  - How can high-temperature plasma and material surfaces co-exist?
    - Micro-electronics processing



Basic Scaling of Turbulent Transport Depends on Eddy Size

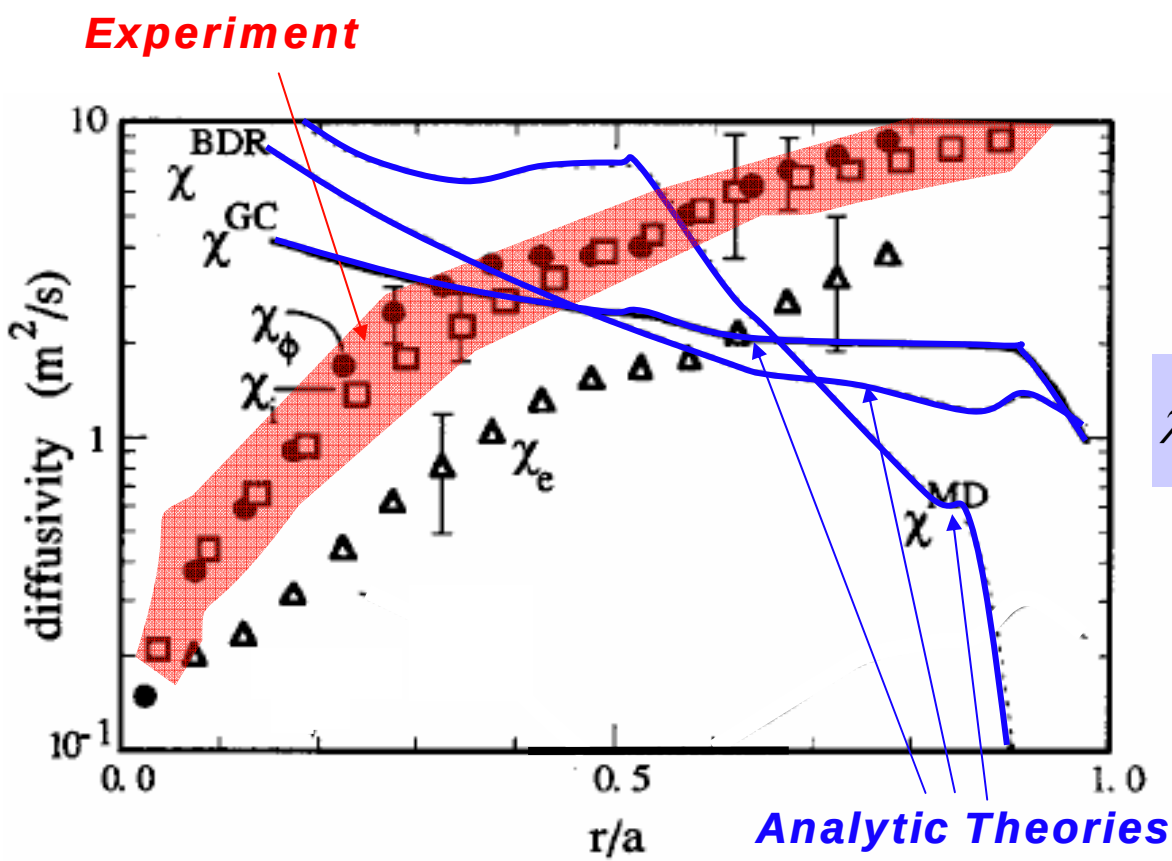
- David Bohm proposed a worst-case thermal diffusion model for plasmas, where eddies are system-scale:

$$v_{E\times B} = k_\perp \tilde{\phi}/B \qquad \tilde{\phi} \sim T/e \qquad \chi \sim v/k_\perp \sim T/eB$$

- The standard "gyro-Bohm" model of strong ion-scale drift-wave turbulence assumes eddies scale as ρ_i :
  - An orbit diffusion model of turbulent saturation gives $\chi \sim \gamma/k_\perp^2$
  - For strong drift waves $\gamma \sim \omega_* \sim k_\perp v_d$;

$$\chi \sim \left(\frac{T}{eB}\right)\left(\frac{\rho_i}{L}\right)$$

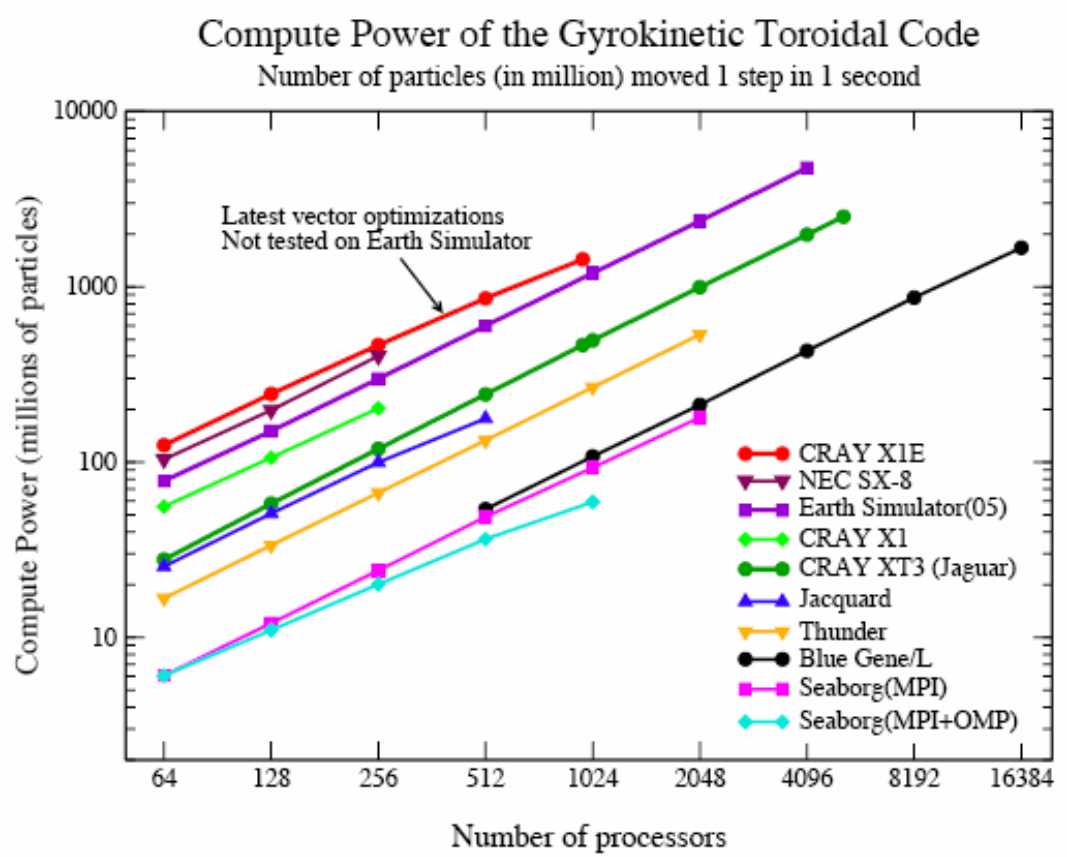
Analytic Gyro-Bohm Theories do Not Capture Radial Dependence of the Experimental χ



$$\chi_{gb} \sim \left(\frac{T}{eB}\right)\left(\frac{\rho_i}{L}\right) \propto T^{3/2}$$

Experimental $\chi_e < \chi_i \sim \chi_\phi$ and general magnitude consistent with ion drift-wave transport, but profiles are far from analytic predictions.

GTC is Aiming to Simulate ITER-size Plasmas

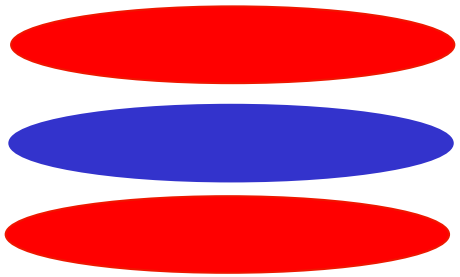


QuickTime™ and a
decompressor
are needed to see this picture.

7.2 Teraflops achieved on Earth Simulator

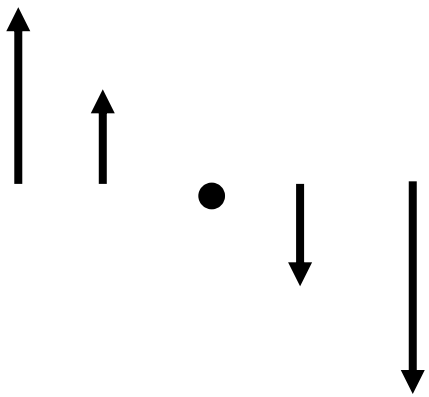
Sheared Flows can Reduce or Suppress Turbulence

Most Dangerous Eddies:
Transport long distances



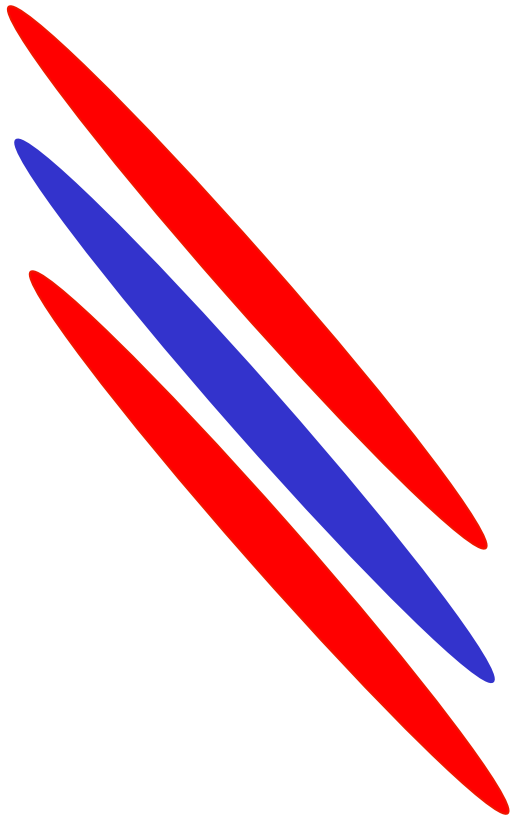
+

Sheared Flows

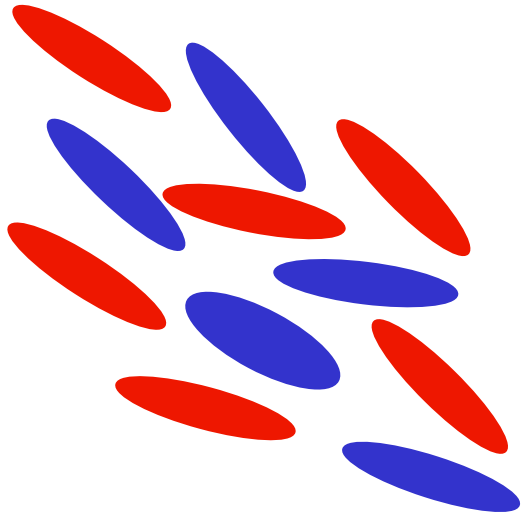


=

Sheared Eddies
Less effective



Eventually break up



$$\omega_{E\times B} \equiv \nabla v_{E\times B} \sim \gamma$$

Direct Measurements of Turbulence Supports Gyro-Bohm + Shear Stabilization Model

- **Movies of turbulent fluctuations in plasma density via beam emission spectroscopy – excitation radiation from beam neutral collisions with plasma ions and electrons.**

(Frame rate: 1,000,000 /sec)

- **Confirms ~ predicted $\delta n/n$ strongest at edge, and weaker in plasma core. Spectrum ~ theory**

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

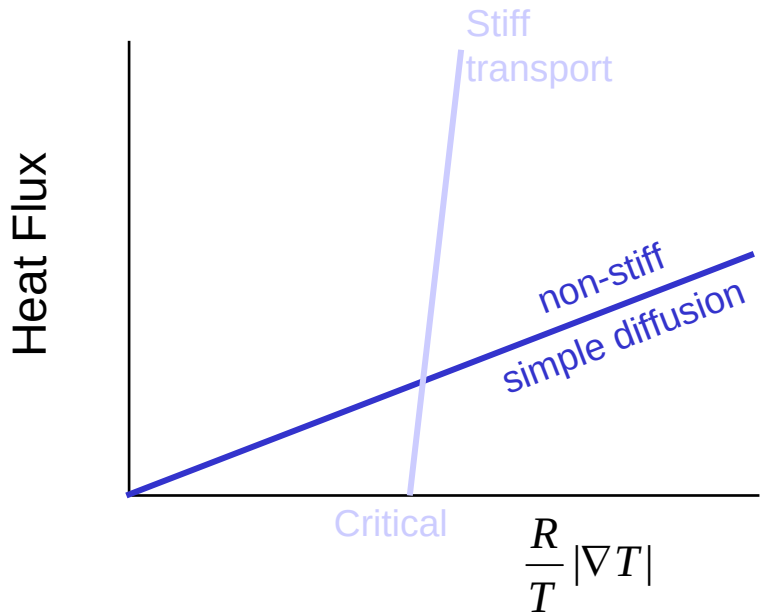
Height

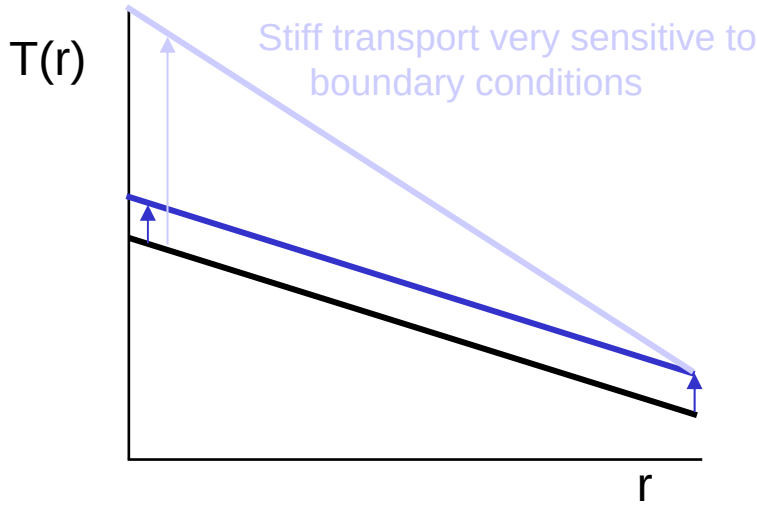
- **Varied flow speed across plasma results in tearing of structures when**

$$\omega_{E\times B} \equiv \nabla v_{E\times B} \sim \gamma$$

Radius

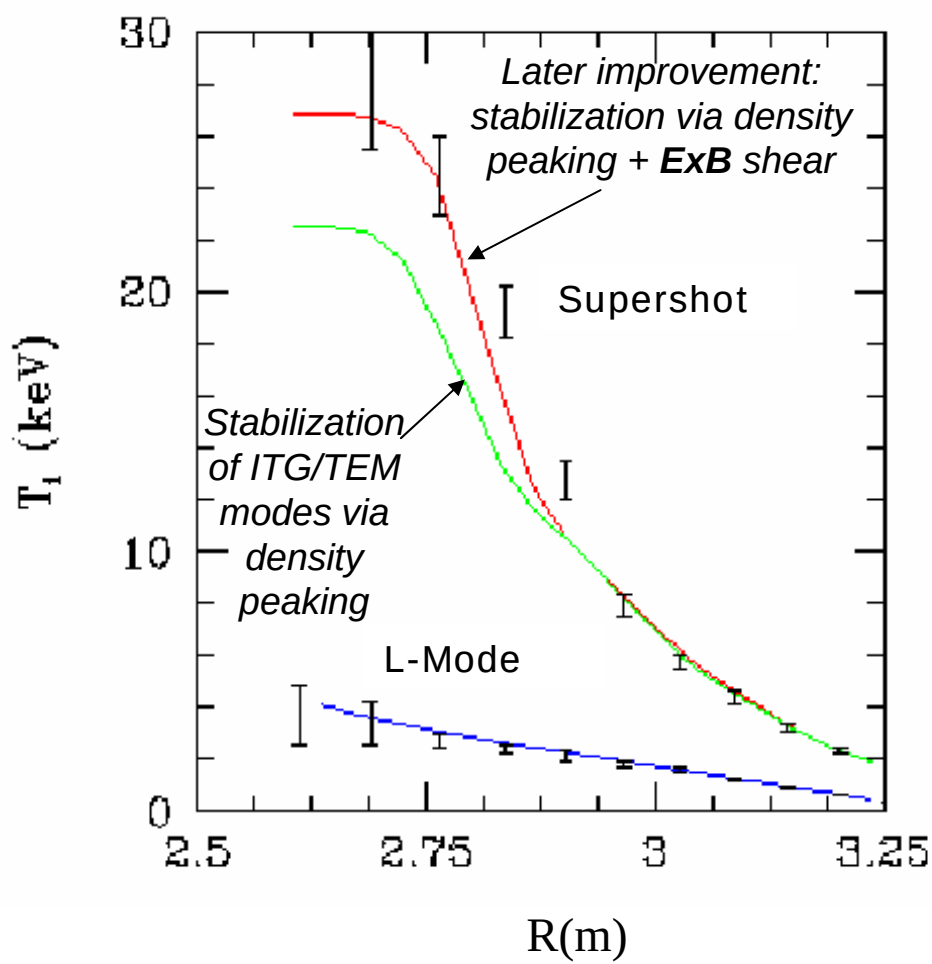
Simulations Indicate that Ion Temperature Gradients must be Close to Marginal Stability





Theory Now gets Temperature Profile Correct!

- **Critical ion temperature gradient depends strongly on density gradient and edge temperature.**
  - **Linear gyrokinetics identify critical gradients.**
  - **Nonlinear code runs map out parametric shape of χ_i.**



Cause of Electron Thermal Transport is not yet Resolved

Ion motion "shorts out" self-driven flows on the electron scale.

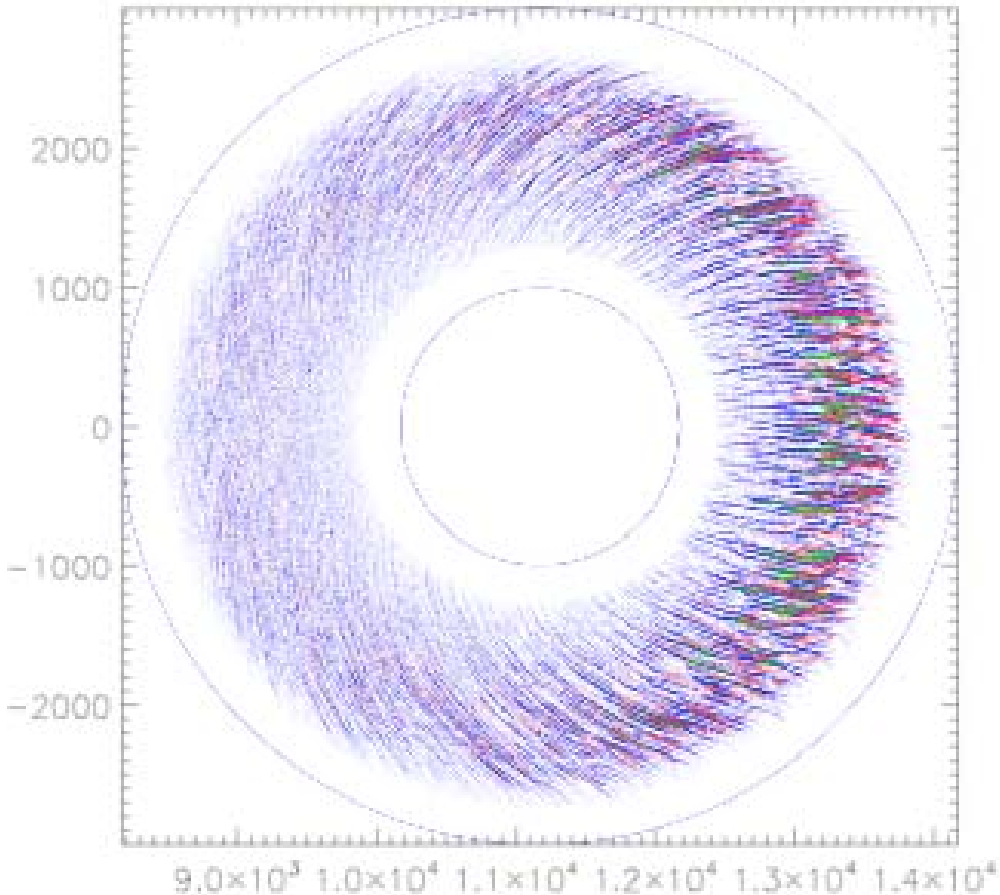
Streamers are long-lived.

Are they intense enough to cause transport?

Or is electron thermal transport due to ion-scale modes?

Occam's razor is a poor guide in plasma physics.

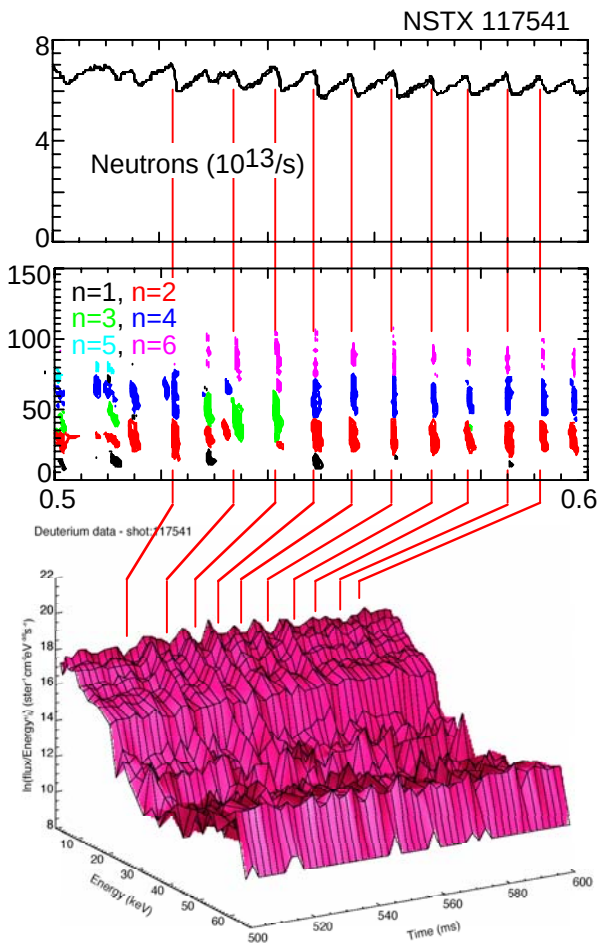
NSTX will make key new measurements this year.



ITER will make Critical Contributions in Each Area of Plasma Science

- **Stability:** Extend the understanding of pressure limits to much larger size plasmas, e.g., NTM meta-stability.
- **Energetic particles:** Study strong heating by fusion products, in new regimes where multiple instabilities can overlap.
- **Turbulence:** Extend the study of turbulent plasma transport to much larger plasmas, providing a strong test of gyro-Bohm physics.
- **Plasma-materials:** Extend the study of plasma-materials interactions to much higher power and much greater pulse length.

These results can be extrapolated via advanced computing to related magnetic configurations.



External heating in current experiments.

Integrated Modeling

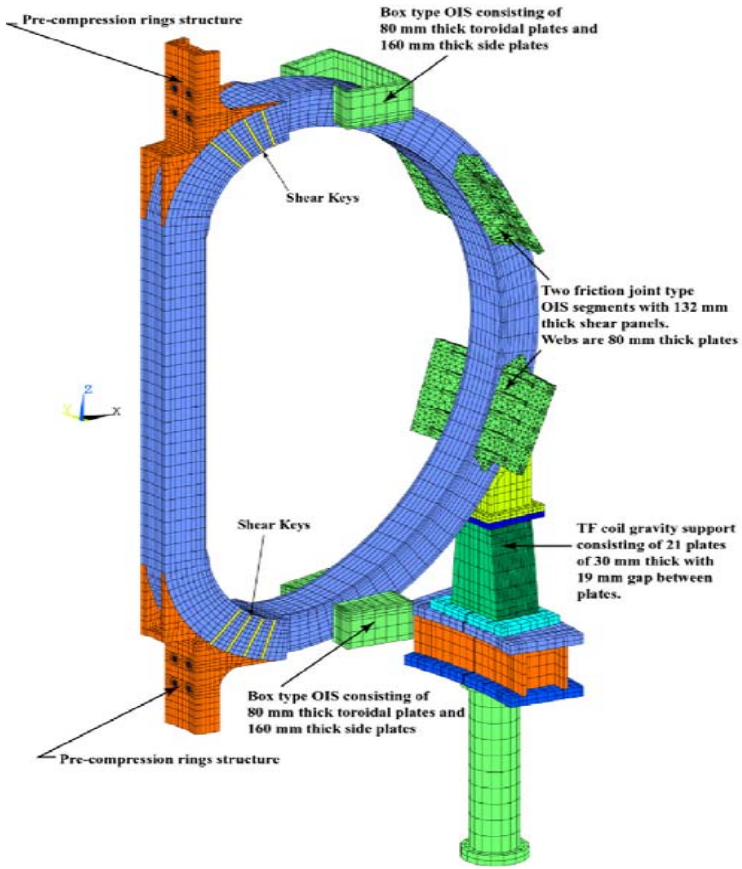
QuickTime™ and a
MPEG-4 Video decompressor
are needed to see this picture.

- TRANSP and TSC being integrated into PTRANSP
  - Analysis code
  - Predictive code
- Fusion Grid enables routine TRANSP analysis at PPPL from off-site.

ITER will Test Fusion Technologies at Power Plant Scale

- **Plasma Vessel Components**
  - 5 MW / m² steady heat flux
  - 20 % duty factor during operation
- **Nuclear Components**
  - Initial test of tritium replenishment by lithium-bearing modules in vessel wall.
- **Superconducting Magnets**
  - Power plant size and field, 40 GJ

These technologies are applicable to all configurations.



ITER Toroidal Field Coil

ITER is a Dramatic Step towards National Demonstration Power Plants

- **ITER is truly a dramatic step. For the first time the fusion fuel will be sustained at high temperature by the fusion reactions themselves.**
  - **Today:** ***10 MW(th) for 1 second with gain ~1***
  - **ITER:** ***500 MW(th) for >400 seconds with gain >10***

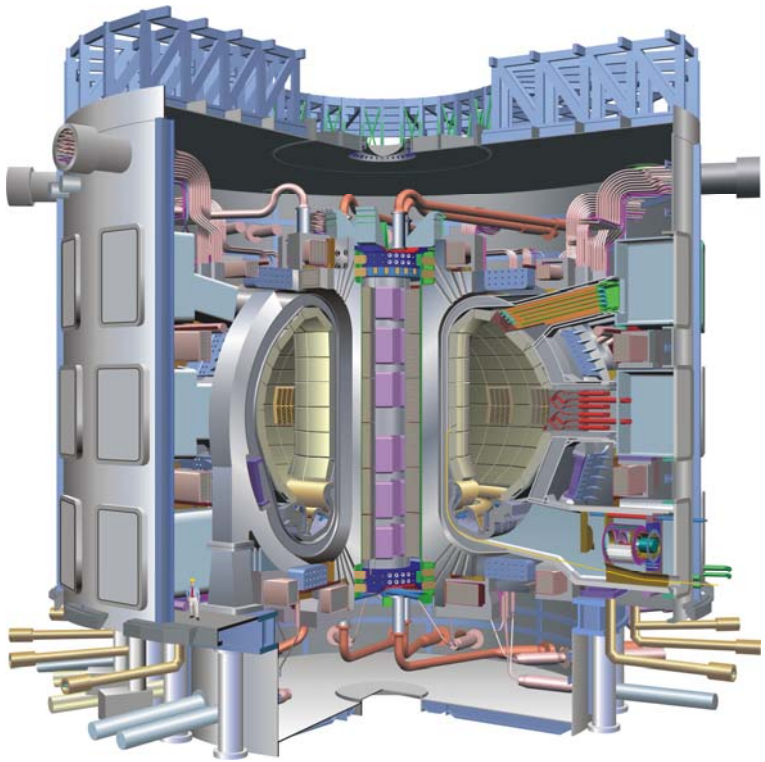
- **Further science and technology are needed.**
  - **Demo:** ***2500 MW(th) continuous with gain >25, in a device of similar size and field as ITER***

  ⇒ **Higher power level**

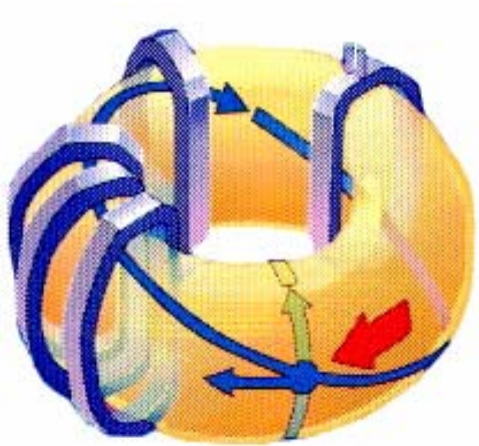
  ⇒ **Efficient continuous operation**

- **Strong, innovative research programs focused around ITER are needed to address these issues.**
  - **Experiments, theory/computation and technology that support, supplement and benefit from ITER.**

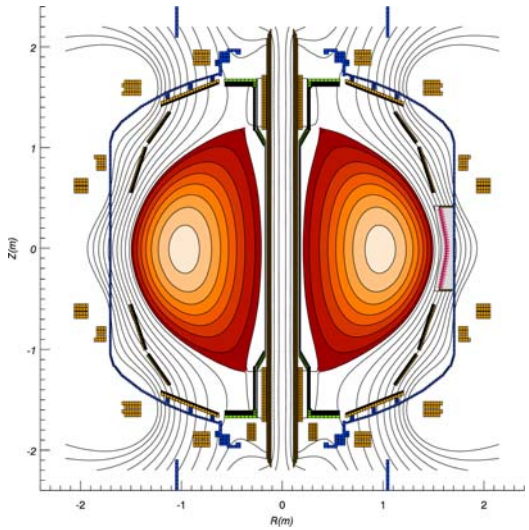
- **ITER will provide the science needed at the scale of a Demonstration Power Plant.**
  - **Whether Demo is configured as an Advanced Tokamak, a Spherical Torus or a Compact Stellarator.**



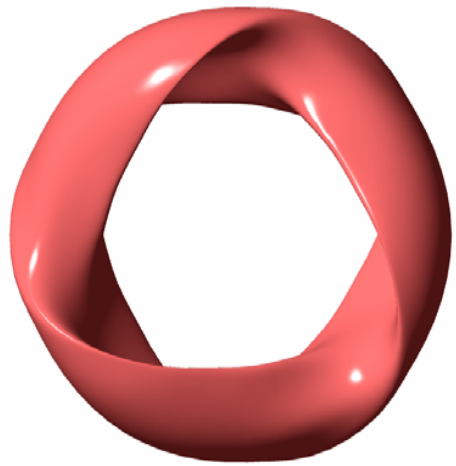
The World is Engaged in Fusion Plasma Science across a Breadth of Configurations



Advanced Tokamak
Active instability control and driven steady-state.



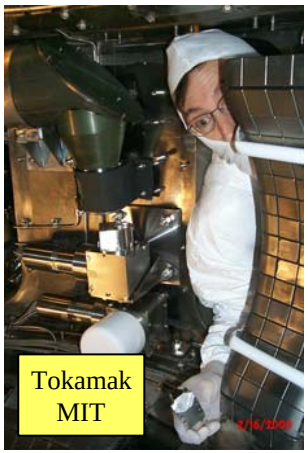
Spherical Torus
High plasma pressure at low magnetic field.

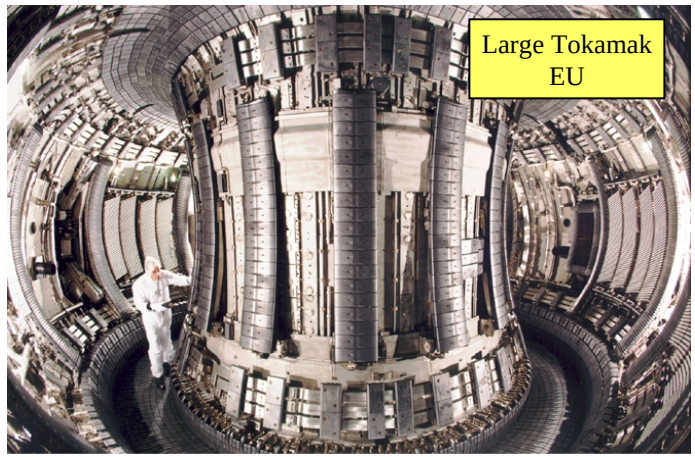


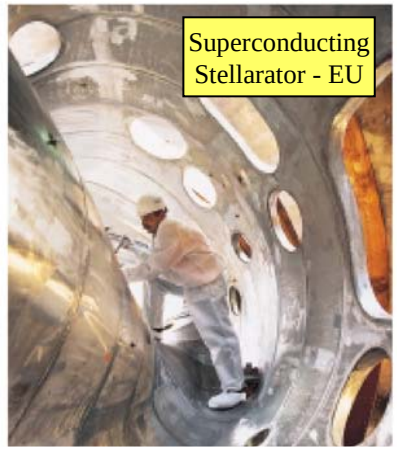
Compact Stellarator
Passive stability and steady-state operation.

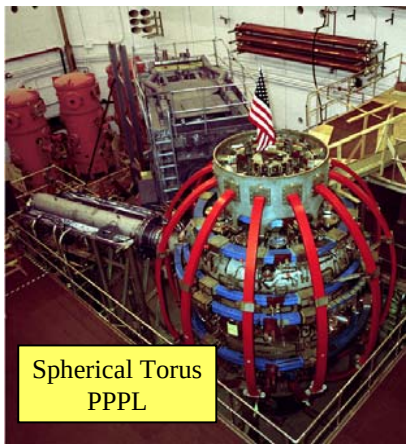
Understanding of a range of configurations is needed to support ITER and to develop practical fusion systems.

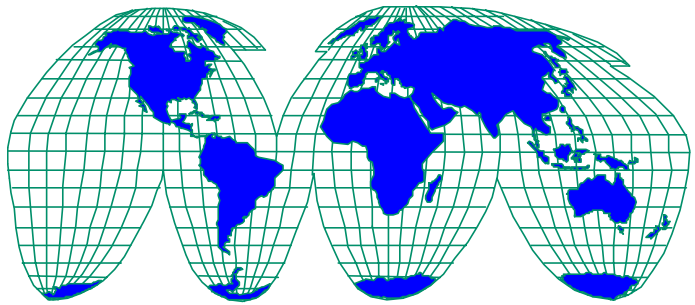
Magnetic Fusion Research is a Worldwide Activity: Optimizing the Configuration for Fusion

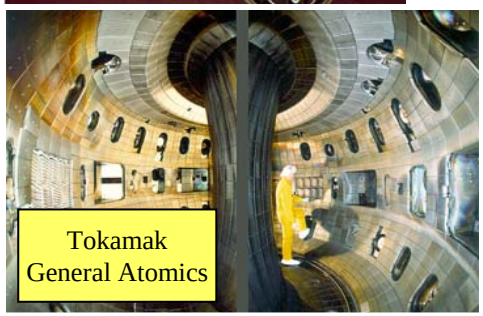


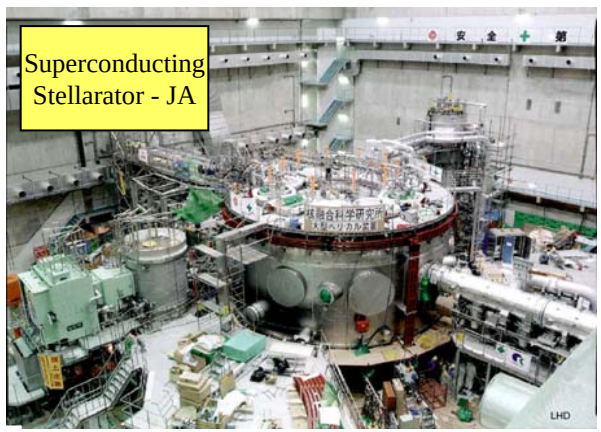


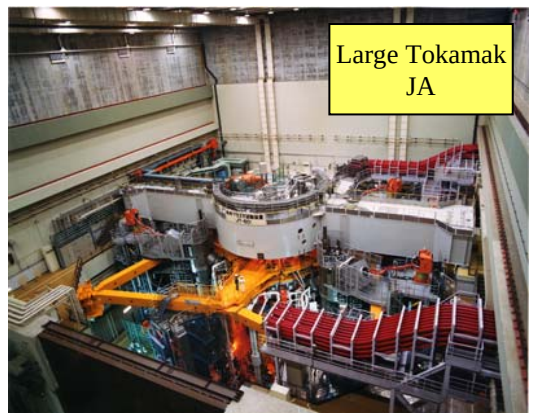












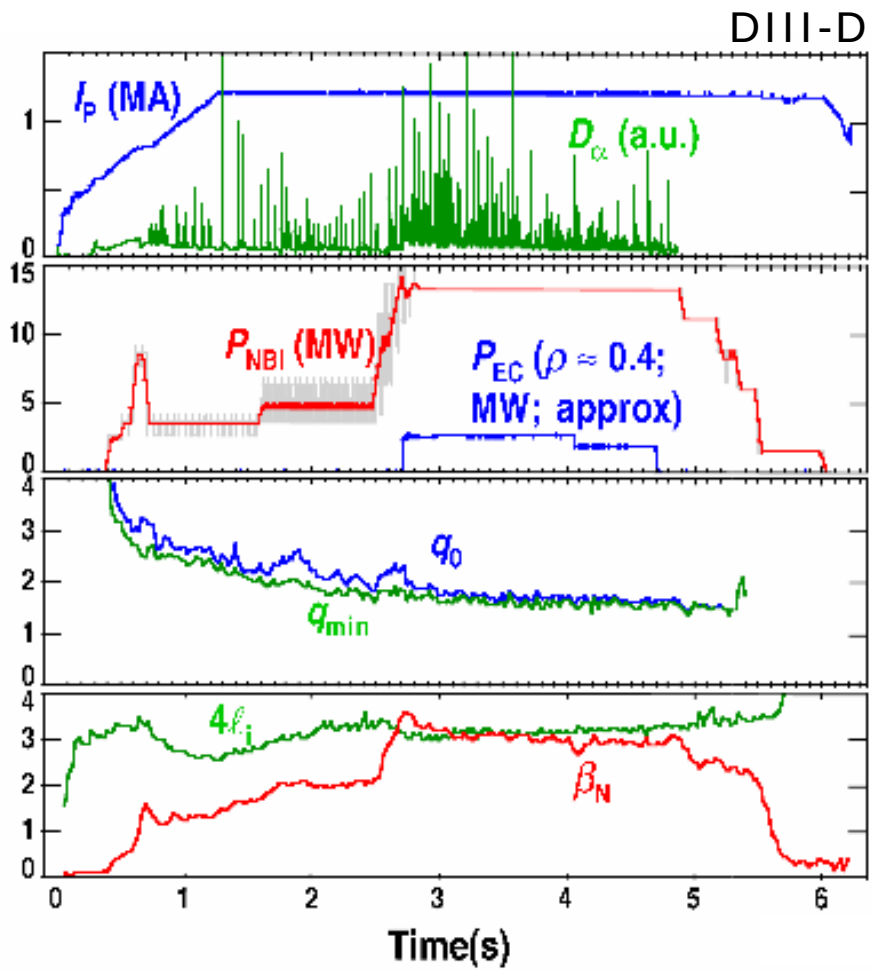
The Steady-State Advanced Tokamak

Strong bootstrap current and external current drive for steady state.

Neoclassical Tearing Mode stabilization.

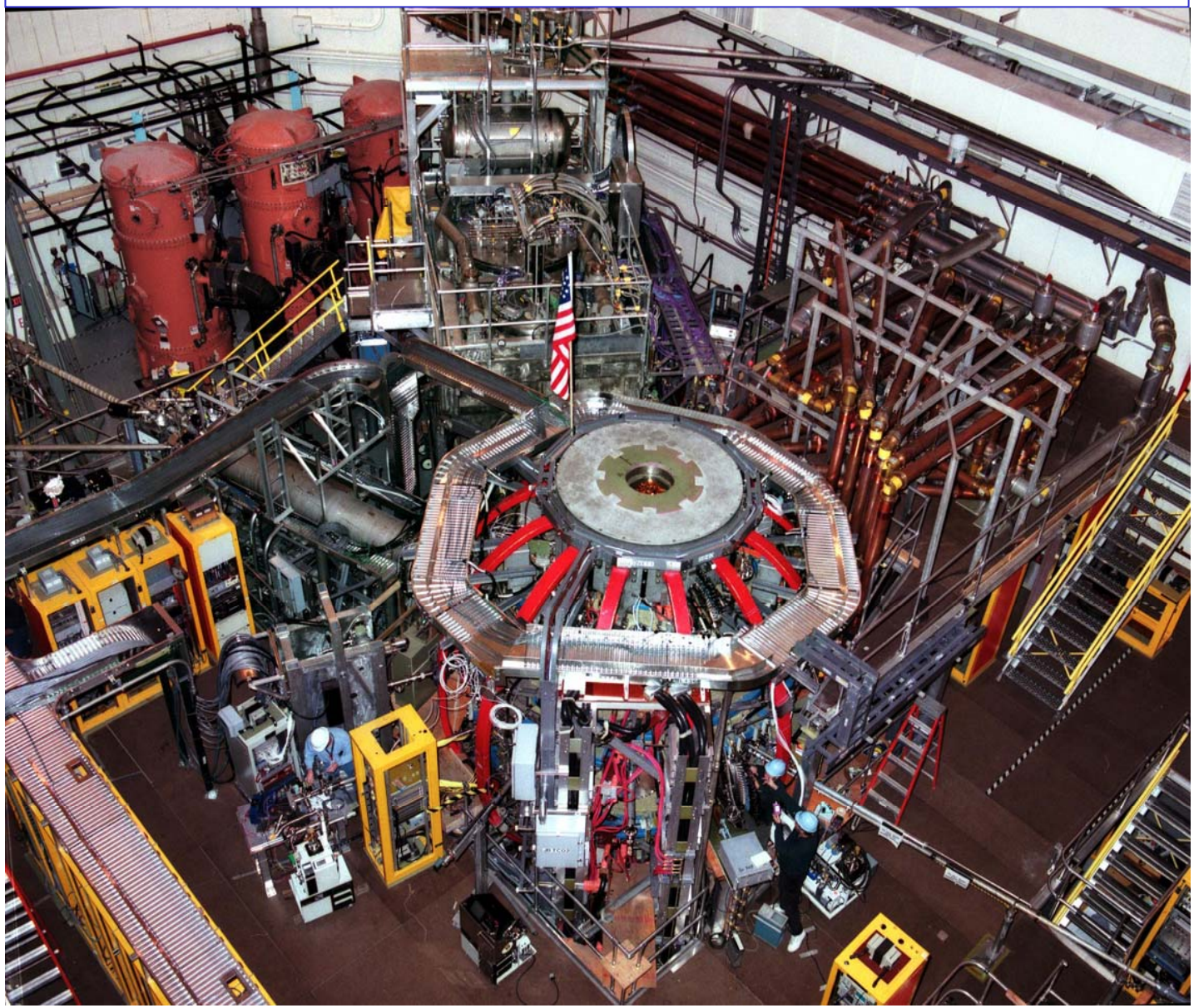
Raise beta limit through Resistive Wall Mode stabilization via rotation and feedback control.

Disruption mitigation.

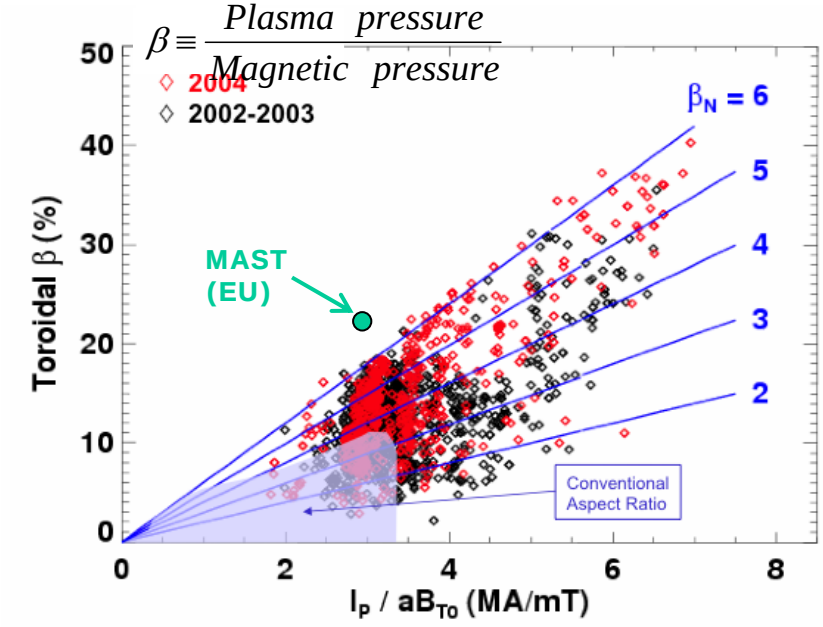


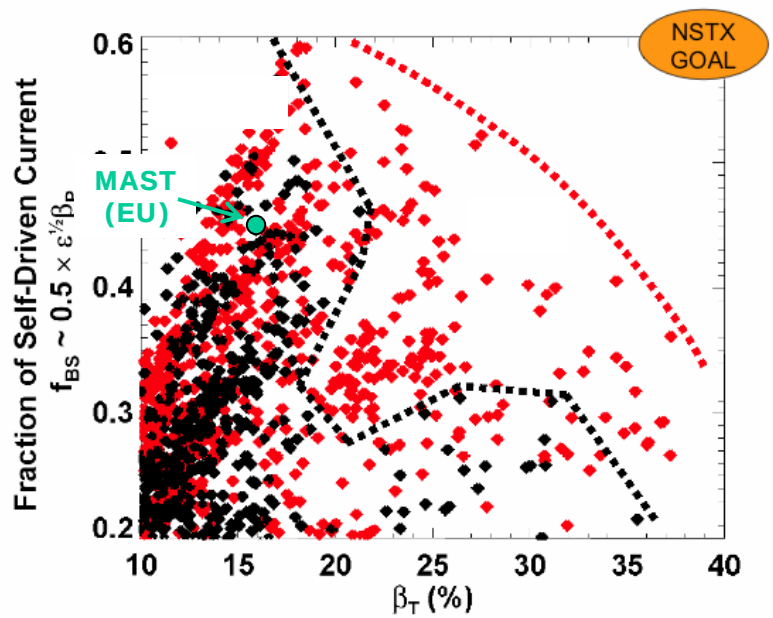
100% non-inductive current sustainment

National Spherical Torus Experiment



The National Spherical Torus Experiment is Leading the World in High β Research

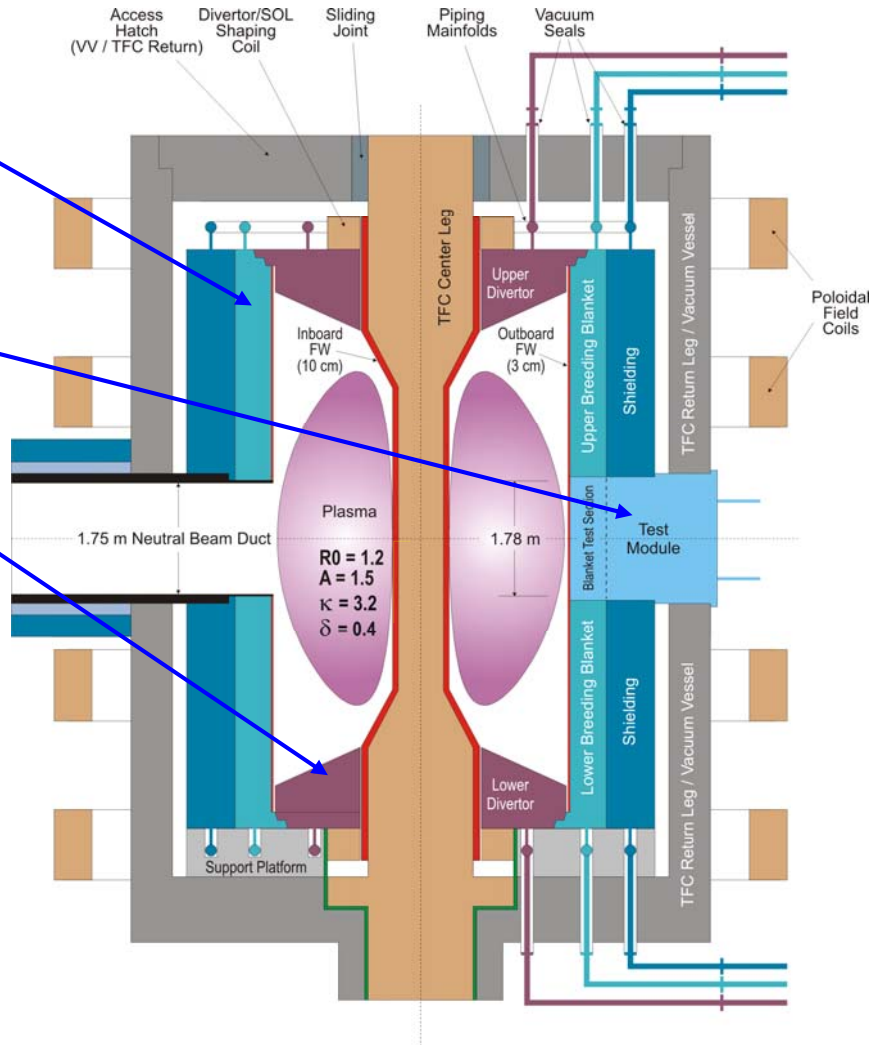




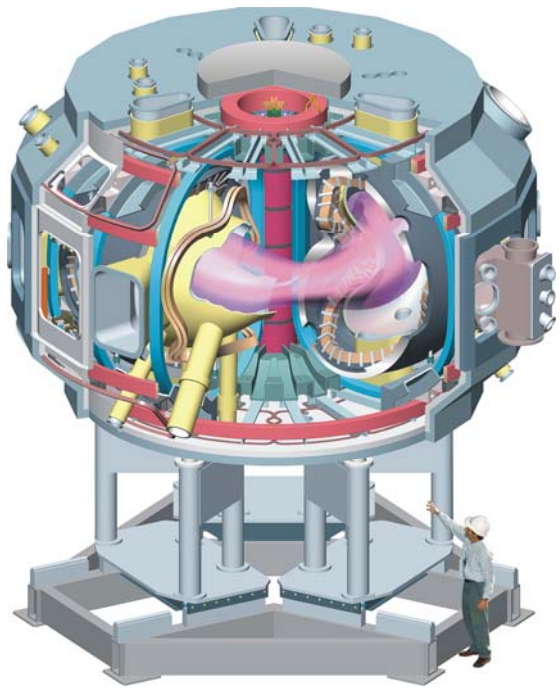
High β is needed for a practical Component Test Facility and Demo Power Plant, and contributes to astrophysics.

The Spherical Torus Leads to a Compact (R ~ 1.2m) High Fluence Component Test Facility

- **Test blankets**
  - Integrated assemblies removed vertically or as modules through mid-plane ports.
- **Divertor**
  - Integrated assemblies removed vertically, or through ports.
- **A compact CTF can test components with available tritium**
  - Demo will burn tritium at 140kg per full-power year
  - CTF will burn tritium at 4.5 kg per full-power year



Stellarators use 3-D Shaping for Steady-State Operation, Low Transport and Global Stability



National Compact Stellarator Experiment

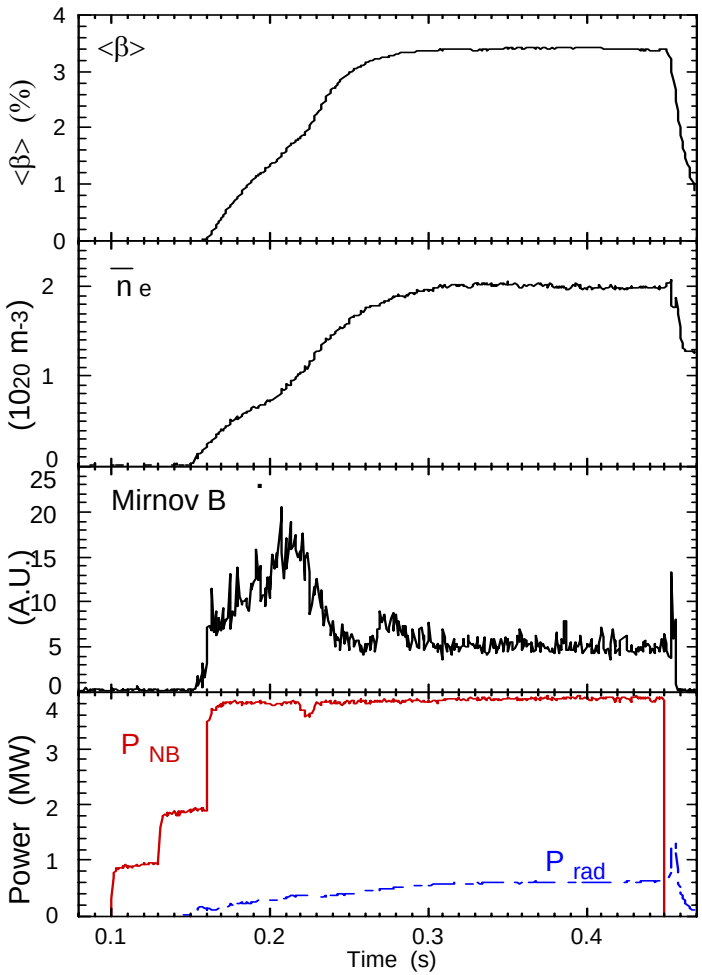
R=1.42m <a>=0.33m

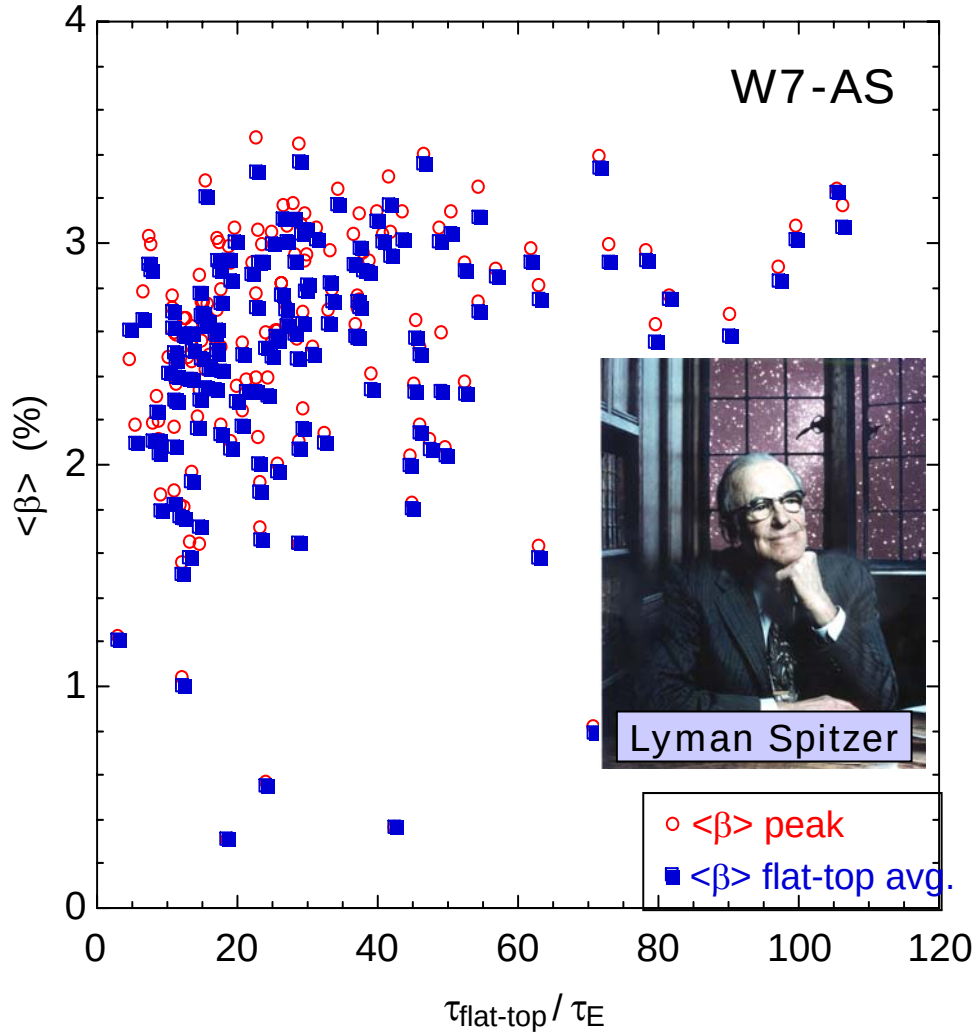
B_t = 2 T, I_p < 350 kA

- Optimization process
  - Built understanding of global stability and turbulence into shape optimizer
  - Massively parallel computing optimized over ~500k configurations
- Optimization result
  - No need for current drive for steady state
  - Compact, enhanced β compared with equivalent tokamak
  - Neoclassical Tearing Mode stable
  - Resistive Wall Mode stable
  - No disruptions

Practical fusion systems must be stable and compact, and must be efficient in continuous operation.

Stellarators make Quiet, Steady Plasmas 30 Minutes on LHD in Japan!





NCSX will make important and unique contributions to ITER: 3-D effects, Flow shear, High density, Energetic particles & ripple.

NCSX Construction is Well Under Way

Vacuum Vessel

Segment #1 of 3
Sealed for Pump-down

Modular Coils

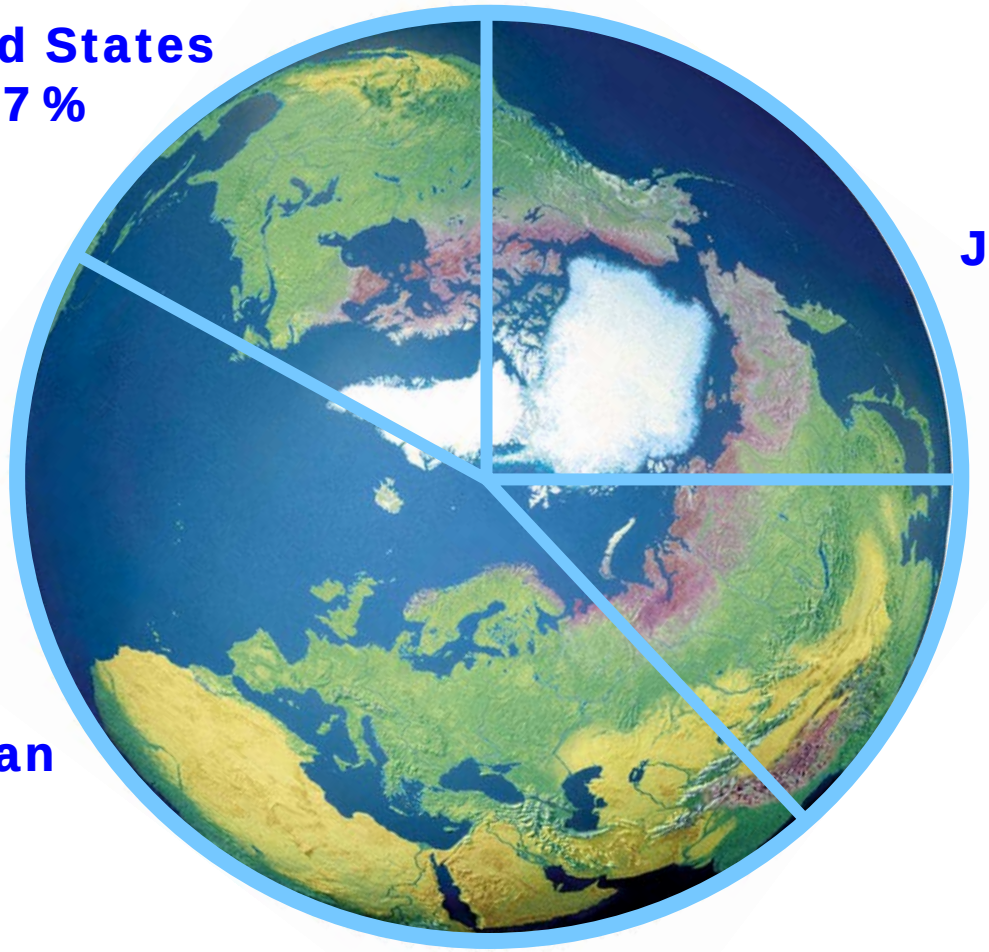
Completed Coil
(#1 of 18)

Construction Will be Completed in 2009

Other Nations are Leveraging ITER Very Strongly

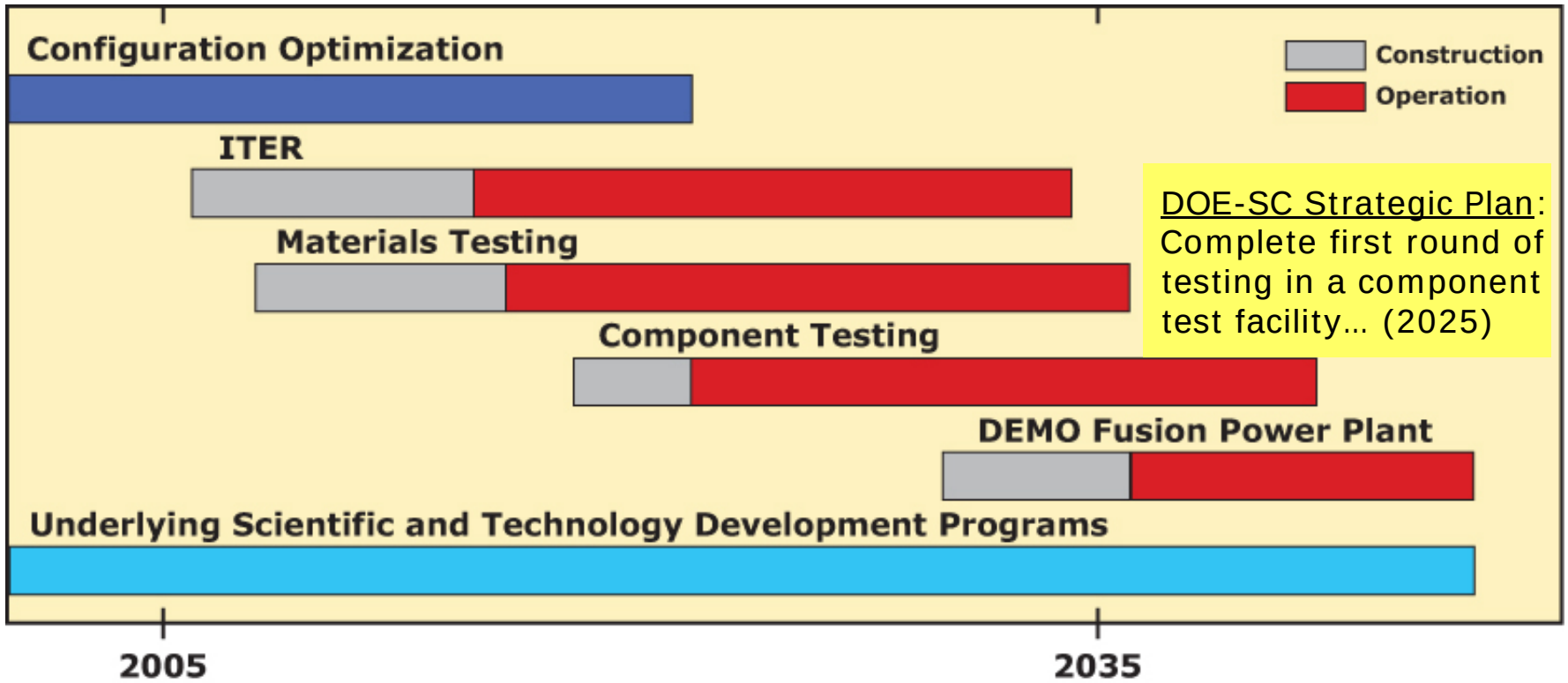
- **Major New Plasma Confinement Experiments**
  - China, South Korea, India, Europe, JA-EU in Japan
  - Each is more costly than anything built in the U.S. in decades.
- **Major Fusion Computational Center**
  - Japan - Europe in Japan
  - Next generation beyond Japan's Earth Simulator
- **Engineering Design / Validation Activity for Fusion Materials Irradiation Facility**
  - Japan - Europe in Japan
  - Critical for testing of materials for fusion systems.
- **A new Generation of Fusion Scientists and Engineers being Trained around the World**
  - Many young non-U.S. scientists and engineers at conferences.
  - China plans to have 1000 graduate students in fusion.

The U.S. is about 1/6 of the World Magnetic Fusion Effort



US: $260M/yr
World: ~$1.5B/yr
(FY 2005)

The U.S. can Take a Leadership Role in Fusion Energy Development



DOE-SC Strategic Plan: Complete first round of testing in a component test facility… (2025)

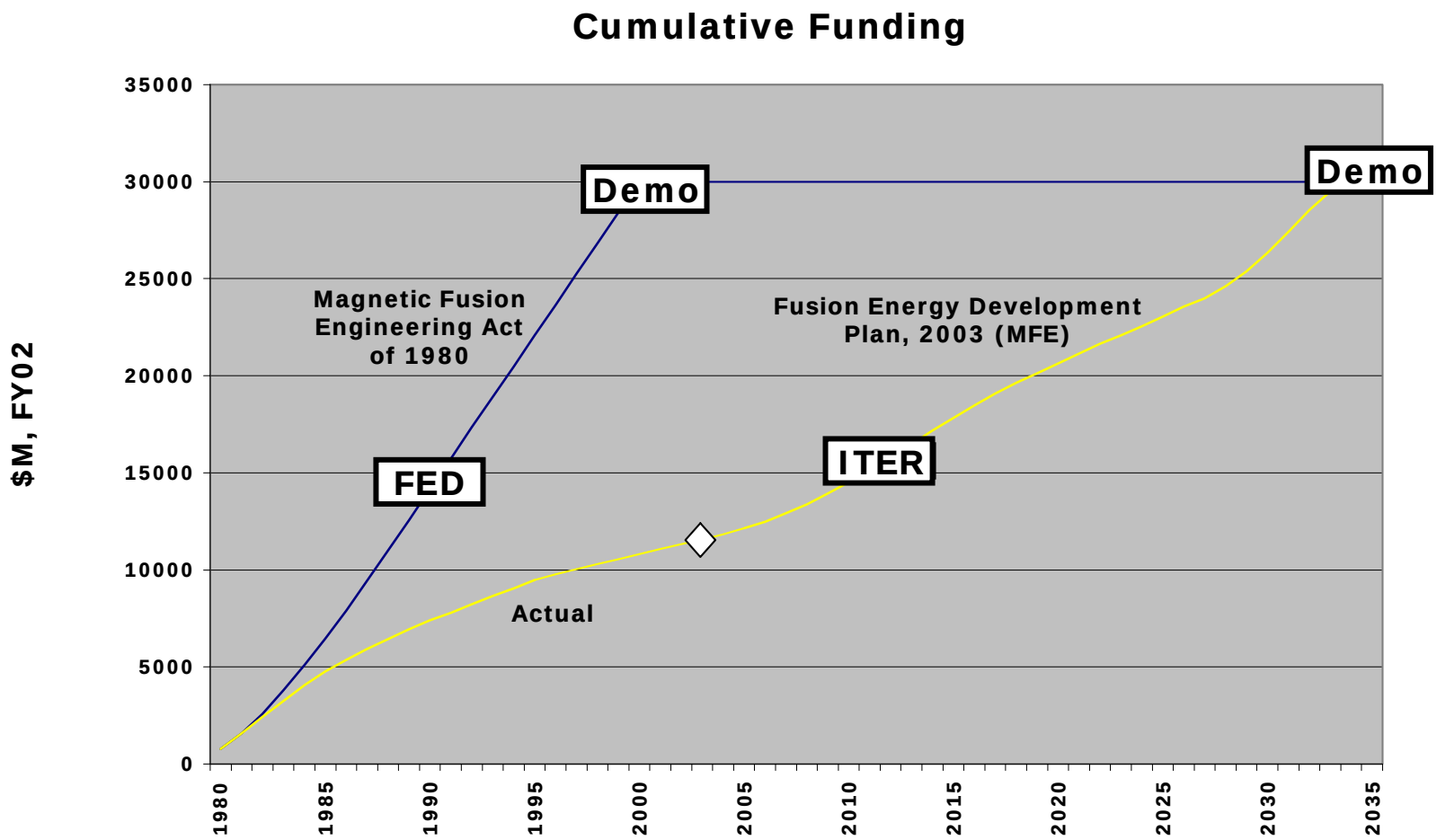
Success in Configuration Optimization and ITER operations will provide the basis for a compact U.S. Component Test Facility, positioning the U.S. for a competitive Demo Power Plant.

Magnetic Fusion Science

- Advances in diagnostics and computation have dramatically increased the understanding of high-temperature magnetically-confined plasmas.
- High-temperature plasma physics is an exciting area of research, with many linkages to other areas of science.
- Recent scientific results have dramatically altered our vision of fusion power systems, and give us confidence that ITER will achieve its goals.
- ITER needs to be leveraged to get to practical fusion energy, and the U.S. can play a critical role.

Backup

The Fusion Energy Sciences Advisory Committee Laid Out a Development Path for Fusion



The estimated development cost for fusion energy is essentially unchanged since 1980.